On a Resequencing Model for High Speed Networks*

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Abstract

In this paper we analyze the effect of fixed delay in conjunction with queueing and resequencing delay on the optimal distribution of traffic on multiple disjoint paths. We study a system of two hosts or end nodes, connected by a high speed network, communicating on two virtual channels which follow disjoint physical paths. The paths have a different number of hops and/or physical length which leads to a different amount of constant delay for each of them. The variable delay on each path is modelled by a queue with exponential service. Furthermore the destination node delivers packets in the order they arrived at the source node, which entails additional resequencing delay. We find the optimal split of traffic, so as to minimize the total average system time (including the resequencing delay). Our results show that the optimal splitting probability may be heavily dependant on the difference in the fixed delays on the two paths. Numerical examples are presented to illustrate the effect of fixed delay on the fraction of traffic routed to different paths. Performance can be further improved when we do a deterministic split of the traffic.

1 Introduction

With the increase in transmission speeds, available bandwidth is also growing steadily. ATM end nodes might communicate with each other using multiple parallel paths/routes constituting a single virtual circuit for various reasons. [1] presented a multiple path approach called the string mode for use in ATM networks to balance the load, wherein an incoming burst was chopped into smaller subbursts and sent on multiple paths. Apart from increased efficiency for bursty traffic, this approach also lowers the blocking probability as the total bandwidth required can be found by splitting this requirement over a set of paths. [2] deals with a parallel communications scheme, and the advantages it offers, in the context of ATM traffic control. A channel coding scheme using multiple parallel paths was considered in [3], which improved the fault tolerance of digital communication networks. One can set up multiple parallel connections to increase the maximum throughput between a pair of nodes and spreading the traffic on multiple paths [10] or because of the unavailability of required bandwidth on one path.

An important issue associated with communications using multiple paths is that of resequencing. As the traffic between a typical pair of end nodes follows different paths, which have different speeds (available bandwidth), packets belonging to a session may arrive out of order at the destination node. The packets arriving out of order may have to wait in a special buffer called the resequencing buffer, before they can be delivered in order to the destination process. Some additional amount of delay is incurred due to this wait in the resequencing buffer. In [4]-[7] several models have been considered by researchers to evaluate the distribution of resequencing delay and total end-to-end delay. Most of these models are of the source node, that is at the edge of a network, or of a single hop. The models considered differ in the number of available channels, the arrival and the service distributions. Simulation studies in [5] have shown, in a case of a two hop network, that for exponentially distributed messages, the end-to-end resequencing strategy gives smaller average resequencing delay as well as total delay than the hop-by-hop resequencing strategy. Probabilistic routing of incoming traffic to a set of parallel queues has been considered in [8, 9] in the context of load balancing/sharing. All these models do not take into account the fixed delays, and hence are applicable to a system within which the fixed delay incurred along the paths is either very small as compared to the queueing delay or is the same for all the paths. Recently in [10] a two node single hop network was analyzed, for routing the traffic on a per connection and per packet basis on the two available paths. [11] considered a system of two high speed hosts connected by a WAN at gigabit speeds, communicating on multiple parallel ATM virtual circuits, with the same available bandwidth on every channel. The incoming packets were distributed in round robin fashion, and packets in parallel channels bypassed each other because of the varying amount of delay in each channel.

The paper is organized as follows. In section 2 we present the motivation for our model. Section 3 deals

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with the evaluation of the average resequencing delay and the total end-to-end delay. The numerical results from our analysis are reported in section 4, followed by our conclusions in section 5.

2 Motivation and Model Description

Previous resequencing models [4]-[7] of multiple parallel paths between source and destination nodes have concentrated on modelling network elements which introduce variable delays. With the increase in network bandwidth, the queueing delay is no more a dominant factor in the total end-to-end delay [14]. In a high speed environment the fixed delay (propagation+fixed processing) along a path is often comparable to or more than typical queueing delay. So the conventional queueing models for analyzing the optimal split of traffic on more than one disjoint paths connecting two stations needs to be suitably modified.

We consider a simple system of two nodes that are connected by two disjoint paths. Each of the paths has a different amount of fixed delay which can be due to the fact that they are of different physical length and/or have different number of hops (entailing varying amounts of propagation delay and fixed processing delay). Furthermore the available bandwidth on the paths may also be different. We model the queueing portion of the delay by an equivalent exponential service rate and the fixed portion of the delay by a delay line. Notice that there can be a number of packets on the fly in the delay line. We assume that the state information, i.e. number of customers in each queue, is not available for routing decisions. So policies like Join the Shortest Queue are not considered. The equivalent optimal routing problem for two heterogeneous links, which does not take into consideration the resequencing delay, is easy to analyze, see for e.g. [13, pp. 453-454]. The main aim of this work is to study the effect of fixed delay on the optimal traffic split for minimizing the total end to end delay (including the resequencing delay) in a high speed environment. For analytical tractability we have modelled the arrival process to be Poisson, though a bursty process would be more appropriate for many source types. Here we analyze a simple system of 2 parallel M/M/1 queues which operate at service rates μ_1 and μ_2, with Poisson arrivals at rate λ. We assume a stable system ($\lambda p < \mu_1$ and $\lambda(1-p) < \mu_2$) with infinite buffers. The delay lines T_1 and T_2 are connected in tandem with server-1 and server-2 respectively. The system schematic is shown in Figure 1. We wish to find an optimal split of traffic with an objective of minimizing the sum of the queueing delay and resequencing delay.

3 Analysis

This section deals with the evaluation of the average resequencing delay and the average time spent in a path. There is a fixed delay of T_1 in the upper path and T_2 in the lower path. We consider probabilistic splitting of traffic, with $p\lambda$ being routed to the first path and $(1-p)\lambda$ takes the second path. An interesting case for study is when the fast path has more

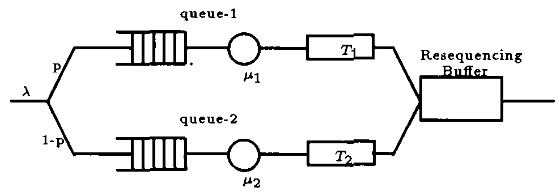

Figure 1. System of parallel M/M/1 queues with delay lines.

fixed delay than the slow path.

3.1 Evaluation of the average time spent by a packet before arriving at the resequencing buffer

As we are doing a probabilistic splitting of the traffic, we can use simple M/M/1 formulae to evaluate the average time spent by a packet between it's arrival into the system to it's arrival into the resequencing buffer. Average time spent in the first and the second path is given by,

$$E[T] = \frac{1}{\lambda}\left[\frac{\lambda p}{\mu_1 - \lambda p} + \frac{\lambda(1-p)}{\mu_2 - \lambda(1-p)} + p\lambda T_1 + (1-p)\lambda T_2\right] \quad (1)$$

The terms $p\lambda T_1$ and $(1-p)\lambda T_2$ are due to the constant delay associated with each path.

3.2 Evaluation of the Resequencing Delay

Here we find an expression for average resequencing delay (RD) experienced by a typical customer called the tagged customer (TC). The approach we take is similar to the one taken in [8]. Upon arrival TC finds the system state to be (m, n), which means TC finds m customers in queue-1 (comprising of buffer-1 and server-1) and n customers in queue-2 (comprising of buffer-2 and server-2). Now, because of the FCFS service discipline, the customers who arrive into system after the TC cannot affect the departure time of TC from the resequencing buffer. Hence only customers which were in the system when TC arrived can potentially contribute to the resequencing delay it suffers. Further, the customers which are already ahead of TC in the queue it joins also cannot contribute to TC's resequencing delay. This means we can find out the RD, conditioned only on the state the TC finds the system in, and the queue which TC joins. One can then find the average expected value of RD by summing over all possible values of (m, n). Thus,

$$RD = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} R(m,n)\ P(m,n) \quad (2)$$

$$R(m,n) = pR^1(m,n) + (1-p)R^2(m,n) \quad (3)$$

where $R^1(m,n)$ and $R^2(m,n)$ is the RD conditioned on the TC joining either queue-1 or queue-2 and the system state being (m,n). $P(m,n)$ is the probability that TC finds the system state to be (m,n). Thus,

$$P(m,n) = (1-\rho_1)(1-\rho_2)\ \rho_1^m\ \rho_2^n \qquad (4)$$

$$\rho_1 = \frac{\lambda p}{\mu_1} \qquad \rho_2 = \frac{\lambda(1-p)}{\mu_2} \qquad (5)$$

For evaluating $R^1(m,n)$ and $R^2(m,n)$, let us assume without loss of generality that $T_1 \geq T_2$. Introducing a delay line is equivalent to shifting the departure processes of the two servers by T_1 and T_2 time units respectively. Thus, it can be seen that the RD is only a function of the difference between T_1 and T_2, and does not depend on their absolute values. The absolute values of T_1 and T_2 affect only the total time required to traverse the first path and the second path respectively. Hence, for the evaluation of RD, we can replace the delay lines by an equivalent delay line of value $T = T_1 - T_2$ in the first path.

Lemma 1: The resequencing delay suffered by a customer depends only on the difference in the fixed delays associated with the paths and not on their absolute values.
Proof: The proof of this lemma is simple and is not presented here for the sake of brevity. The detailed proof can be found in [15].

3.2.1 Evaluation of $\mathbf{R^1(m,n)}$

If the TC joins queue-1, the system state becomes $(m+1,n)$. Clearly, if $n=0$ then TC does not suffer any RD. Now for TC to leave queue-1 (i.e. TC arrives at the start of the delay line), there have to be $m+1$ service completions at queue-1. From the point of view of the TC, only the departure time of the customer who was in n^{th} position in queue-2, at the time of it's arrival, is important. So if there are n or more service completions at queue-2, during the time for $m+1$ service completions at queue-1, then the RD is zero. If the number of service completions at queue-2 is i and $\alpha = \frac{\mu_1}{\mu_1+\mu_2}$ then,

$$q(m+1,i) = \binom{m+i}{i} \alpha^{m+1}(1-\alpha)^i,$$

$$for \quad 0 \leq i \leq n-1 \ and\ n > 0 \qquad (6)$$

is the probability of m service completions at queue-1, i service completions at queue-2 followed by service completion of the TC. So there are $n-i$ customers still in queue-2 at TC's service completion, which have T time units to finish their service and not affect TC's departure. If there are customers present in queue-2, then departures from queue-2 are Poisson with rate μ_2. Hence, if we find exactly j Poisson points in the interval T, then there are j additional service completions in time T. Which means the TC will have to wait in the resequencing buffer only for $n-i-j$ service completions at the second server. Hence the resequencing delay will be,

$$R^1(m,n) = \sum_{i=0}^{n-1} \binom{m+i}{i} \alpha^{m+1}(1-\alpha)^i$$

$$\left(\sum_{j=0}^{n-i} Pr(N(T)=j)\ \frac{n-i-j}{\mu_2} \right) \qquad (7)$$

where $Pr(N(T)=j)$ is the probability of finding exactly j Poisson points in the interval T, which is given by,

$$Pr(N(T)=j) = \frac{(\mu_2 T)^j\ e^{-\mu_2 T}}{j!} \qquad (8)$$

3.2.2 Evaluation of $\mathbf{R^2(m,n)}$

Here we analyze RD, conditioned on TC's joining queue-2 and the system state being (m,n). Depending upon the values of (m,n) and the number of service completions at queue-1, we have to consider the following different cases.

Case *a*) System state (m,n), $m>0$ and less than m service completions at queue-1:

If the TC joins queue-2, the system state becomes $(m,n+1)$. For the TC to arrive into the resequencing buffer, there have to be $n+1$ service completions at queue-2, during which there can be i service completions at queue-1. If at least one of the m customers is still in queue-1, then we know the expected RD with the available information. So, if there are i (for $0 \leq i \leq m-1$ and $m>0$) service completions at queue-1 then the TC will have to wait in the resequencing buffer for $\frac{m-i}{\mu_1} + T$ units of time. Summing over all i, the average expected RD is given by,

$$R^{2a}(m,n) = \sum_{i=0}^{m-1} \binom{n+i}{i} \alpha^i(1-\alpha)^{n+1} \left(\frac{m-i}{\mu_1} + T\right) \qquad (9)$$

Case *b*) System state (m,n), $m>0$ and exactly m service completions at queue-1:

We have to consider the case of exactly m service completions at queue-1 separately. This is because if all the m customers have already finished their service before the TC finished it's service then the m^{th} packet can either be anywhere on the delay line or it might have already left the system. In the first case the TC suffers some RD but in the later case it does not. Again the probability of $m-1$ service completions at queue-1, i service completions at queue-2 followed by the m^{th} service completion at queue-1, is given by,

$$q(m,i) = \binom{m+i-1}{i} \alpha^m(1-\alpha)^i \qquad (10)$$

So with probability $q(m,i)$, at the instant when the m^{th} customer reaches the delay line, i customers from queue-2 have already finished their service and are either in the resequencing buffer or have left the system (for $0 \leq i \leq n$), the $n+1^{st}$ being the TC. So there are still $n+1-i$ customers in queue-2. The TC will suffer some RD only if the cumulative service times of all these $n+1-i$ customers is less than T. This means evaluating the sum of $n+1-i$ i.i.d. exponential random variables which we shall denote by x, conditioned on the event that the sum is less than T.

The expected value of a random variable x (with (n+1-i)-stage Erlang distribution with parameter μ_2) conditioned on the event that $x \le T$ is given by,

$$E[x|x \le T] = \frac{\frac{n+1-i}{\mu_2}\left(1 - e^{-\mu_2 T}\sum_{k=0}^{n+1-i}\frac{(\mu_2 T)^k}{k!}\right)}{1 - e^{-\mu_2 T}\sum_{k=0}^{n-i}\frac{(\mu_2 T)^k}{k!}} \tag{11}$$

So the units of time TC will have to wait in the resequencing buffer is given by, $(T - E[x|x \le T])\ Pr(x \le T)$. $Pr(x \le T)$ is simply given by the denominator of the above equation. Summing over all the possible different number of service completions at queue-2, we get the average expected RD for this case.

$$R^{2b}(m,n) = \sum_{i=0}^{n}\binom{m+i-1}{i}\alpha^m(1-\alpha)^i \left(T - \frac{n+1-i}{\mu_2}\,\frac{1 - e^{-\mu_2 T}\sum_{k=0}^{n+1-i}\frac{(\mu_2 T)^k}{k!}}{1 - e^{-\mu_2 T}\sum_{k=0}^{n-i}\frac{(\mu_2 T)^k}{k!}}\right)(1 - e^{-\mu_2 T}\sum_{k=0}^{n-i}\frac{(\mu_2 T)^k}{k!}) \tag{12}$$

If there are $n+1$ service completions at queue-2, then the TC does not suffer any RD.

Case *c*) System state $(0,n)$:

The TC can also suffer some resequencing delay if it finds the system state to be $(0,n)$ and it joins queue-2. In such a case, the TC may have to wait for a customer which got served on server-1 but was in the delay line at the instance of the TC's arrival. To evaluate the expected RD in this case, we have to know the position of the last customer in the delay line. In this scenario, we can view the position of the last customer on the delay line, as randomly picking a point in the idle period of server-1. The idle duration of server-1 is exponentially distributed with parameter λp. The forward and the backward recurrence times [12, pp. 302-304] in the case of a random point in an interevent time (which is exponentially distributed with parameter λp), are also exponentially distributed with parameter λp. Thus the last customer has already traversed a portion of the delay line, which can be represented by an exponential random variable x with parameter λp. RD will be 0 if $x > T$, i.e. the last customer has traversed the complete delay line. We define random variable $z = (x + y_1 + y_2 + \ldots + y_{n+1})$ where y_i's are the random variables corresponding to the service times of customers at server-2 and x corresponds to the portion of delay line already traversed by the last customer. The RD will be,

$$R^{2c}(0,n) = (T - E(z \mid z \le T))\ Pr(z \le T) \tag{13}$$

The density functions of x and $y_{(n+1)} = (y_1 + y_2 + \ldots + y_{n+1})$ are,

$$f_x(x) = \lambda_1 e^{-\lambda_1 x} \tag{14}$$

where $\lambda_1 = \lambda p$.

$$f_{y_{(n+1)}}(y_{(n+1)}) = \frac{(\mu_2 y)^n}{n!}\,\mu_2 e^{-\mu_2 y} \tag{15}$$

Convolving the above two densities we obtain the density for random variable z (for the case $\lambda_1 \ne \mu_2$) to be,

$$f_z(z) = \lambda_1 e^{-\lambda_1 z}\left(\frac{\mu_2}{\mu_2 - \lambda_1}\right)^{n+1}\left(1 - \sum_{i=0}^{n}\frac{([\mu_2 - \lambda_1]z)^i}{i!}e^{-(\mu_2-\lambda_1)z}\right) \quad for\ \lambda_1 \ne \mu_2 \tag{16}$$

The case $\lambda_1 = \mu_2$ will be considered separately. The expression for $E(z \mid z \le T)$ is given by,

$$E(z \mid z \le T) = \frac{1}{F_z(T)}\left(\left(\frac{\mu_2}{\mu_2 - \lambda_1}\right)^{n+1}\left(\frac{1 - e^{-\lambda_1 T}}{\lambda_1} - Te^{-\lambda_1 T}\right) - \lambda_1\sum_{i=0}^{n}\frac{i+1}{\mu_2^2}\left(\frac{\mu_2}{\mu_2 - \lambda_1}\right)^{n+1-i}\left[1 - \sum_{j=0}^{i+1}\frac{(\mu_2 T)^j}{j!}e^{-\mu_2 T}\right]\right) \tag{17}$$

and the expression for $F_z(T) = Pr(z \le T)$ is given by,

$$Pr(z \le T) = \left(\frac{\mu_2}{\mu_2 - \lambda_1}\right)^{n+1}(1 - e^{-\lambda_1 T}) - \sum_{i=0}^{n}\frac{\lambda_1}{\mu_2}\left(\frac{\mu_2}{\mu_2 - \lambda_1}\right)^{n+1-i}\left[1 - \sum_{j=0}^{i}\frac{(\mu_2 T)^j}{j!}e^{-\mu_2 T}\right] \tag{18}$$

$R^{2c}(0,n)$ can then be calculated using equations (17), (18) and (13). Equations (16), (17) and (18) are valid only for $\lambda_1 \ne \mu_2$. For the case $\lambda_1 = \mu_2$ the distribution of z will be,

$$f_z(z) = \frac{(\mu_2 z)^{n+1}}{n+1!}\mu_2\, e^{-\mu_2 z} \tag{19}$$

Proceeding on the same lines as above, we get,

$$F_z(T) = Pr(z \le T) = 1 - e^{-\mu_2 T}\sum_{k=0}^{n+1}\frac{(\mu_2 T)^k}{k!} \tag{20}$$

and

$$E(z \mid z \leq T) = \frac{1}{F_z(T)} \frac{n+2}{\mu_2} \left(1 - e^{-\mu_2 T} \sum_{k=0}^{n+2} \frac{(\mu_2 T)^k}{k!} \right) \quad (21)$$

$R^{2c}(0,n)$ can then be calculated using equations (20), (21) and (13).

Using equations (2), (3), (7), (9), (12) and (13) we get an expression for average expected resequencing delay.

$$RD = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} [p\, R^1(m,n)\, P(m,n)] + (1-p)\ \left([R^{2a}(m,n) + R^{2b}(m,n)] P(m,n) + R^{2c}(0,n) P(0,n) \right)$$

4 Numerical Results and Discussion

This section discusses the numerical results based on the analytical expressions obtained in the preceding section. With the help of some numerical examples, we illustrate the effect of constant delay on the fraction of traffic routed to different paths. Depending upon the values of available bandwidth on each channel and the constant delays, we consider two different cases ($\mu_1 = \mu_2$ and $\mu_1 \neq \mu_2$, for different values of T). Interesting variations to be considered are when the input load can be carried by a single path and when it cannot be carried by any one of the two paths. This demonstrates the use of multiple paths for load balancing only and when the required bandwidth is unavailable on a single link, respectively.

The typical values of service rates we have considered are 6.25 pkts/msec, which corresponds to available bandwidth of 50 Mbps for a packet size of 1000 bytes (or 5 Mbps for a packet size of 100 bytes) and 0.625 pkts/msec which corresponds to available bandwidth of 5 Mbps for a packet size of 1000 bytes (or 500 Kbps for a packet size of 100 bytes). The typical value for propagation delay across North America is around 15 msec. If we have a backbone WAN with a fair amount of connectivity, then we assumed that the fixed delays along the two paths can vary by 1 to 5 msec.

We observe that the splitting probability is not only dependant on the service rates and the fixed delays on the two paths but also on the input load. So for a given set of $\rho_1 = \lambda/\mu_1$, $\rho_2 = \lambda/\mu_2$ and T, there exists a value of p ($0 \leq p \leq 1$), which can be used to split the incoming traffic on the two available paths.

4.1 Same available bandwidth on both paths ($\mu_1 = \mu_2 = \mu$):

Here we assume that the same amount of bandwidth is available on both paths. Let us define $\rho = \lambda/(\mu_1 + \mu_2)$. We consider the following subcases depending upon the values of μ and ρ.

4.1.a) Parameter set: $\mu_1 = \mu_2 = 6.25$, $\rho = 0.5$ and $T = 5, 3, 1$

In Figures 2,3 and 4 we plot the resequencing delay and the total end-to-end delay as a function of the splitting probability. It has been shown in [8] that for the case of equal service rates the optimal splitting probability (p^*) is 0.5, for all the feasible values of input load. Referring to [8], we see that for the case $\mu_1 = \mu_2$, the resequencing delay starts increasing as we start using the second path. It reaches a maximum value at $p = 0.5$ and then by symmetry it starts decreasing again. With the presence of T in one path, we can see that a skew is introduced in the plot for RD. This is because the presence of T effectively makes one path slower as compared to the other. Also note that as we reduce T from 5 to 1, the peak in RD approaches $p = 0.5$. The p^* is quite different than that in [8], i.e. 0.5. As expected, we can notice from these figures that the value of p^* is approaching 0.5 as we reduce T from 5 to 1. Notice that for higher values of fixed delays the value of p^* is as low as 0.075 (for $T = 5$, implying the use of a single path to carry most of the load). There is a significant improvement in the end-to-end delay values at optimal p (p^*) over the value at $p = 0.5$ (i.e. p^* with $T = 0$ as in [8]).

4.1.b) Parameter set: $\mu_1 = \mu_2 = 6.25$, $\rho = 0.45$ and $T = 1$

Figure 5 depicts the plot of p versus total delay, for the case in which each of the paths can carry the load individually. We get an improvement in end-to-end delay when we do a traffic split. Notice that the total delay at p^* is better than the values of total delay if we route all the traffic to a single path ($p = 1$) or if we split traffic according to [8], i.e. using $p^* = 0.5$. It was also noticed that the presence of $T = 5$ and $T = 3$ makes one path so much slower than the other, that we do not get much improvement by doing a traffic split. For these cases the reduction in the time spent on the other path, only marginally outweighs the resequencing delay introduced by splitting the traffic.

4.1.c) Parameter set: $\mu_1 = \mu_2 = 0.625$, $\rho = 0.375$ and $T = 5, 3$

If the service rates are reduced by a factor of 10 (i.e. $\mu_1 = \mu_2 = 0.625$), then the effect of T is less pronounced for the same value of ρ, i.e. 0.5 (as in case 4.1.a). Though p^* is still different from 0.5, there is no significant improvement in the value of total delay at p^* over the value at $p = 0.5$. If we reduce the value of ρ to 0.375, then the value of p^* drifts further away from 0.5. This is shown in Figures 6 and 7.

If we reduce the service rates further by a factor of 10 i.e. $\mu_1 = \mu_2 = 0.0625$ (typical for the current generation packet switched networks), then the effect of T is negligible for the values of $\rho = 0.5$, 0.375 and 0.25, with T ranging up to 5 ms.

The examples above demonstrate the effect of T on the fraction of traffic routed to a path. It is also seen that the changes in the values of end-to-end delays were dependant on the set (λ, μ and T). The presence of T effectively makes one of the paths slower than the other. Therefore for higher service rates and ρ, more traffic gets routed to the path without T (4.1.a and 4.1.b). Also if both the paths can individually carry the load, then high values of T might keep the slow path unused as noted in 4.1.c. We noticed that for some values of T, ρ_1 and ρ_2, the optimal routing strategy is to send all the traffic on one path. One would still want to do a traffic split in the above case if the cost criteria were not to minimize delay (including the resequencing delay) but to increase fault tolerance or to do an even spread of traffic.

Using simulation studies we also show that the end-to-end delay values can be further improved upon by a deterministic split of the incoming traffic. We define a period of a deterministic schedule ($N = n_1 + n_2$) to be a sequence of consecutive n_2 packets to be sent on one path followed by n_1 packets to the other path. As N increases, we noted that the queueing delay increased but the resequencing delay decreased. So one has to choose the period so as to gain in the above tradeoff. n_1/N is chosen to be close to p^*. We observed that for a different set of input parameters and split probability, we get different values of N for better performance. The dependance of N on the above parameters, as well as a determination of the optimal schedule needs to be further investigated.

4.2 Different available bandwidth on the two paths:

Another interesting case for study is when the available bandwidth on both the links is different and the fast link also has more fixed delay. In this case also the constant delay on a path plays a major role in evaluating the quality of the path. It was also observed in [8], that for any given utilization more traffic needs to be sent to the fast server. Referring to the plot of p^* as a function of $\alpha = \mu_1/\mu_2$ in [8], it is seen that for the values of $\alpha = 2$ and 4, all the traffic is routed to the path with more bandwidth for values of ρ up to 0.3 and 0.55 respectively. This study shows that in high speed WANs even if there is more available bandwidth on a path, it may still not be used as the primary path (i.e. path which carries the most of input load). We illustrate this effect with the help of Figures 8 and 9. The parameter set for these plots is ($\lambda = 2.8125$, $\mu_1 = 6.25$, $\mu_2 = 3.125$ and $T = 3, 1$). Here, for $T = 3$, most of the load is carried by the path with $\mu_2 = 3.125$.

Next we consider the case of a higher value of α and when the slow path alone cannot carry all the load by itself. We get some improvement in the total end-to-end delay values by splitting traffic with p^* over sending all the traffic on the fast path, i.e. using $p = 1$ as in [8]. The parameter set for this plot in Figure 10, is ($\lambda = 1.5625$, $\mu_1 = 6.25$, $\mu_2 = 1.5625$ and $T = 5$). For higher values of ρ, one may have less flexibility in the choice of sending traffic on different routes. For the values of $\lambda = \mu_1 = 6.25$, $\mu_2 = 3.125$ and $T = 5, 3, 1$, no significant improvement was noticed in the delay values over those with using p^* as in [8].

The last case which we consider is that of the slow path having more fixed delay than the fast path. In this case also the routing decisions are affected by the amount of constant delay on the slow path. Consider a parameter set of ($\lambda = 5.625$, $\mu_1 = 3.125$, $\mu_2 = 6.25$ and $T = 3, 1$). It can be seen from Figure 11, that for the value of $T = 3$, we do not use the slow path at all. For $T = 1$ we get an improved performance by doing path splitting. Again referring to [8] for this set of parameters the value of p^* is 0.25 for $T = 0$. For $T = 1$, we get a slight improvement in the value for end-to-end delay over values at $p = 0$ (no splitting) and at $p = 0.25$.

5 Conclusions

With the increase in network speeds the fixed delay has become comparable to the queueing delay, hence it can no longer be ignored while evaluating routing policies which take resequencing delays into account. In this paper we have developed a model which takes into account the fixed delay (propagation delay+fixed processing) along a path. We have studied the effect of fixed delay on the optimal split of traffic. The results indicate that the optimal split is very much dependant on the difference in the fixed delays on the two paths, in addition to the bandwidth available on the paths. Simulation studies show that the end-to-end delay values can be further reduced if the traffic is distributed deterministically.

References

[1] J.H. Déjean, L. Dittmann and C. N. Lorenzen, "String Mode-A New Concept for Performance Improvement of ATM Networks," *IEEE Journal on Selected Areas in Communications,* Vol. SAC-9, pp. 1452-1460, No. 9, December 1991.

[2] T.T. Lee and S.C. Liew, "Parallel Communications for ATM Network Control and Management," *Proc. of GLOBECOM'93,* pp. 442-446, November 1993.

[3] E. Ayanoglu, I. Chih-Lin, R.D. Gitlin and J.E. Mazo, "Diversity Coding: Using Error Control for Self-healing in Communication Networks," *Proc. of IEEE INFOCOM'90,* pp. 95-104, June 1990.

[4] I. Iliadis and L.Y. -C. Lien, "Resequencing Delay for a Queueing System with Two Heterogeneous Servers Under a Threshold Type Scheduling," *IEEE Transactions on Communications,* Vol. COM-36, No. 6, pp. 692-702, June 1988.

[5] T.S.P. Yum and T.Y. Ngai, "Resequencing of Messages in Communication Network," *IEEE Transactions on Communications,* Vol. COM-34, pp. 143-149, No. 2, Feb. 1986.

[6] S. Chowdhury, "An Analysis of Virtual Circuit with Parallel links," *IEEE Transactions on Communications,* Vol. COM-39, pp. 1184-1188, No. 8, August 1991.

[7] S. Chowdhury, "Distribution of the Total Delay of Packets in Virtual Circuits," *Proc. of IEEE INFOCOM'91,* pp. 911-918, April 1991.

[8] I. Iliadis and L.Y. -C. Lien, "Resequencing in Distributed Systems with Multiple Classes," *Proc. of IEEE INFOCOM'88,* pp. 881-888, March 1988.

[9] A. Jean-Marie, "Load Balancing in a System of Two Queues with Resequencing," *Performance'87,* Amsterdam, The Netherlands, North Holland, 1988, pp. 75-88.

[10] R. Krishnan and J.A. Silvester, "Choice of Allocation Granularity in Multipath Source Routing Schemes," *Proc. of IEEE INFOCOM'93,* pp. 322-329, March 1993.

[11] N.T. Plotkin and P.P. Varaiya, "Performance Analysis of Parallel ATM Connections for Gigabit Speed Applications," *Proc. of IEEE INFOCOM'93,* pp. 1186-1193, March 1993.

[12] K.S. Trivedi, ***Probability and Statistics with Reliability Queueing and Computer Science Applications,*** Prentice Hall Inc., Englewood Cliffs, 1982.

[13] D. Bertsekas and R.G. Gallagher, ***Data Networks, Third Edition,*** Prentice Hall Inc., Englewood Cliffs, 1992.

[14] K. Hajikano, K. Murakami, E. Iwabuchi, O. Isono and T. Kobayashi, "Asynchronous Transfer Mode Switching Architecture for Broadband ISDN - Multistage Self-routing Switching (MSSR)," *Proc. of IEEE ICC'88,* pp. 911-915, June 1988.

[15] N. Gogate and S.S. Panwar, "On a Resequencing Model for High Speed Networks," *Technical Report TR 94-70,* Dept. of Electrical Eng., Polytechnic University, Brooklyn, NY.

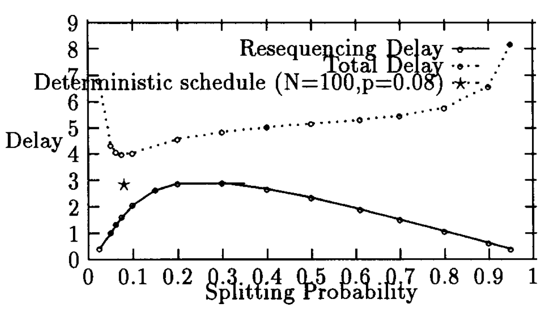

Figure 2. Splitting Probability Vs. Delay
Parameters:
$\lambda = 6.25$ $\mu_1 = 6.25$ $\mu_2 = 6.25$ $T_1 = 5$ $T_2 = 0$

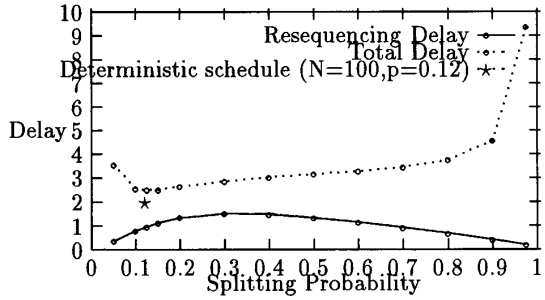

Figure 3. Splitting Probability Vs. Delay
Parameters:
$\lambda = 6.25$ $\mu_1 = 6.25$ $\mu_2 = 6.25$ $T_1 = 3$ $T_2 = 0$

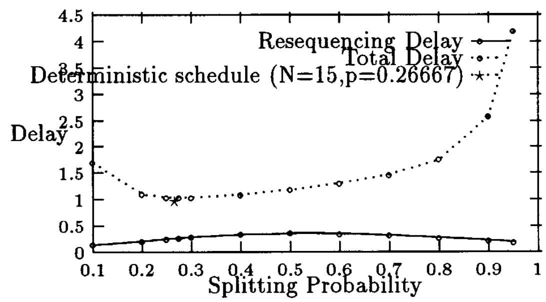

Figure 4. Splitting Probability Vs. Delay
Parameters:
$\lambda = 6.25$ $\mu_1 = 6.25$ $\mu_2 = 6.25$ $T_1 = 1$ $T_2 = 0$

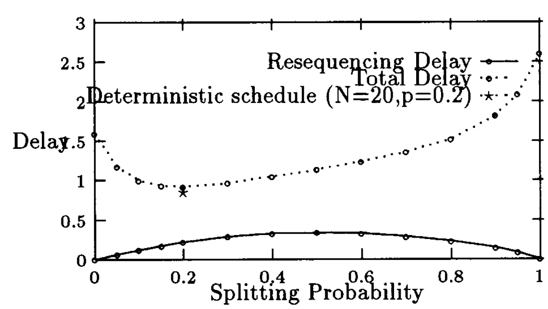

Figure 5. Splitting Probability Vs. Delay
Parameters:
$\lambda = 5.625$ $\mu_1 = 6.25$ $\mu_2 = 6.25$ $T_1 = 1$ $T_2 = 0$

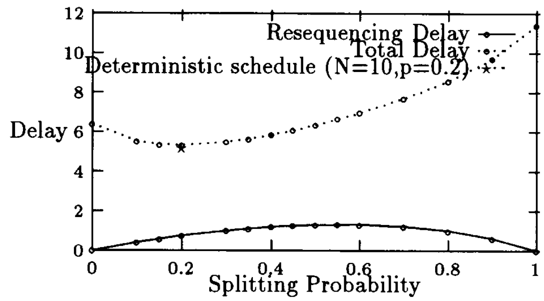

Figure 6. Splitting Probability Vs. Delay
Parameters:
$\lambda = .46875$ $\mu_1 = .625$ $\mu_2 = .625$ $T_1 = 5$ $T_2 = 0$

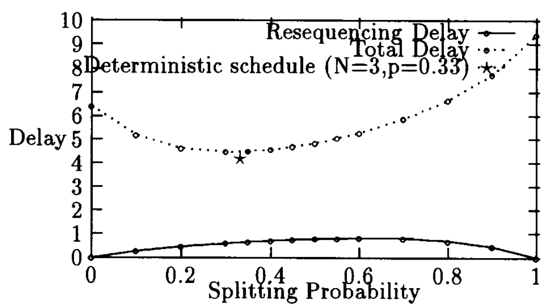

Figure 7. Splitting Probability Vs. Delay
Parameters:
$\lambda = .46875$ $\mu_1 = .625$ $\mu_2 = .625$ $T_1 = 3$ $T_2 = 0$

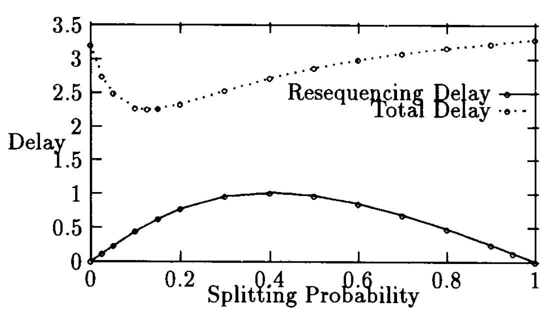

Figure 8. Splitting Probability Vs. Delay
Parameters:
$\lambda = 2.8125$ $\mu_1 = 6.25$ $\mu_2 = 3.125$ $T_1 = 3$ $T_2 = 0$

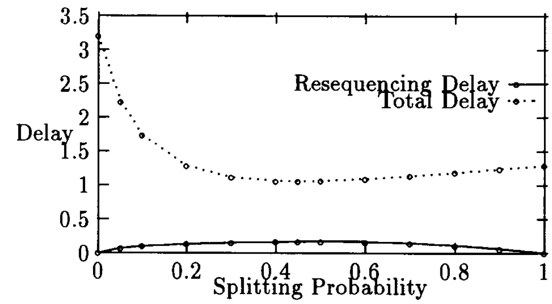

Figure 9. Splitting Probability Vs. Delay
Parameters:
$\lambda = 2.8125$ $\mu_1 = 6.25$ $\mu_2 = 3.125$ $T_1 = 1$ $T_2 = 0$

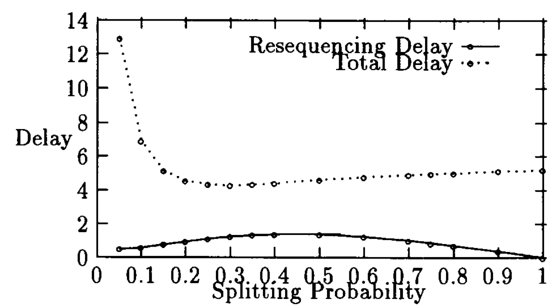

Figure 10. Splitting Probability Vs. Delay
Parameters:
$\lambda = 1.5625$ $\mu_1 = 6.25$ $\mu_2 = 1.5625$ $T_1 = 5$ $T_2 = 0$

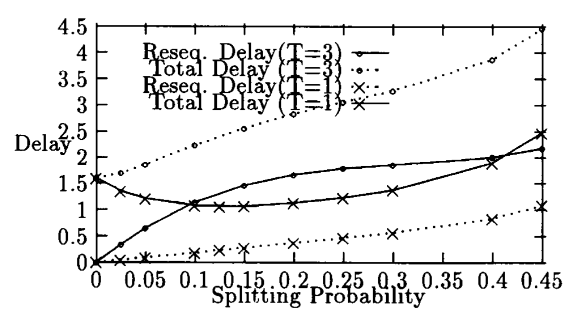

Figure 11. Splitting Probability Vs. Delay
Parameters:
$\lambda = 5.625$ $\mu_1 = 3.125$ $\mu_2 = 6.25$ $T_1 = 3, 1$ $T_2 = 0$